LLNL-TR-666664

Measuring Cross-Section and Estimating Uncertainties with the fissionTPC

N. Bowden, B. Manning, S. Sangiorgio, B. Seilhan

January 30, 2015

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

NIFFTE Uncertainty Working Group

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Feb 2015

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for the NIFFTE Collaboration

February 8, 2015

1 Introduction

The purpose of this document is to outline the prescription for measuring fission cross-sections with the NIFFTE fissionTPC and estimating the associated uncertainties. As such it will serve as a work planning guide for NIFFTE collaboration members and facilitate clear communication of the procedures used to the broader community.

This document extends previous work [1] and discussions within the collaboration on the fissionTPC analysis. Over the past few years, the collaboration has indeed gained a deeper understanding regarding the operation of the fissionTPC and its implications for the data analysis. The development of the data reconstruction software, the simulation efforts, and the analysis of data collected in 2012-2014 has played a key role in addressing many aspects of the analysis. In addition, the collaboration also interacted extensively with the Nuclear Fission community and the project's reviewers, clarifying its work and receiving valuable feedback. This document aims therefore at capturing in a written form this increased understanding of the fissionTPC analysis.

The NIFFTE experiment aims at measuring the energy-differential fission cross-sections in ^{239}Pu with a total uncertainty below 1% for incident neutron energies between 0.1 and 25 MeV. Existing measurements of this quantity show a spread that is largely inconsistent with the uncertainty associated with each individual measurement, hinting at potentially uncontrolled sources of systematic uncertainties. In order to reach its accuracy goal, the NIFFTE collaboration decided to approach the measurement orthogonally with respect to previous work:

- by reducing the number of assumptions in the experimental design and analysis in favor of direct measurement of all the relevant quantities pertaining the cross-section of interest;
- by utilizing a new detection technology, a fissionTPC, rather than the fission chambers that have been the workhorse so far in the field.

The fissionTPC is a Time Projection Chamber that has been customized and tuned to incorporate a fissionable target, introduced in a neutron beam, and be sensitive to the interactions from protons to alphas to fission fragments. The fissionTPC delivers full 3D reconstruction of each fission event and provides several associated event quantities in addition to the energy and time-of-flight that are the only output of fission chambers. Details on the fissionTPC detector are described in [2].

Given the novelty of the experimental apparatus and approach, since early on the collaboration has recognized the importance of careful validation of the detector response as well as the analytical methods. Several such measurements are incorporated in the NIFFTE experimental program. The isotropic distribution of fission fragments arising from ^{252}Cf spontaneous fission decays provides an ideal metric to validate one of the most critical aspects of the fissionTPC operation, namely particle track reconstruction. Similarly, the alpha-to-fission decay branching ratio provides a validation for the efficiency in detecting alphas and fission fragments. In this document, we will explicitly link these validation measurements to the final cross-section measurement goal of the project. Similarly, the new fission cross-section measurement technique being introduced here will be validated by using the fissionTPC to measure the ^{238}U/^{235}U ratio, for which the analysis is not complicated by the high rate of α emission of ^{239}Pu.

Absolute measurement of a fission cross-section is extremely challenging and experimentalists resort to measure cross-sections as a ratio relative to a standard isotope in order to simplify the problem. Similarly, the NIFFTE collaboration will initially aim at measuring ^{239}Pu/^{235}U ratio. However, since the cross-section for neutron-induced fission in ^{235}U is only known to the precision of 1% [3], the collaboration aims at measuring also the ^{239}Pu/^{1}H ratio to take advantage of the well understood and more accurately measured cross-section for H(n,el). The measurement against ^{1}H comes with its own challenges both in the experiment and the analysis. We will only briefly mention some of these later in this document; the collaboration will develop a more detailed understanding at a later date.

Along with measuring the cross-section ratios, the collaboration focuses on providing an accurate and thorough analysis of the associated uncertainties. Given the complexity, this work will be performed in steps, with an initial focus on the largest uncertainties in previous experiments, namely the beam and target uniformity, and the identification of fission fragments over other particles. This will be the focus of the analysis for FY15. The analysis will be later extended to provide detailed uncertainties of all components of the cross-section.

The document is structured as follows. In section 2 we review the formulation for extracting cross-sections using the fissionTPC. We then provide an overview of the analysis steps in section 3. Each step is described in more detail in the following sections 4–7. Section 8 outlines the role of the simulation work in support of the analysis. Concluding remarks are given in section 9.

2 Cross-sections for the fissionTPC

The measurement of cross sections using the fissionTPC share some of the characteristic steps used in previous work with fission chambers [4]. The fissionTPC however is experimentally more complex and explicitly attempts to measure quantities that were subject to assumptions in fission chamber work. Therefore, the method to extract the cross section differs in several key aspects that are outlined here.

The starting point for determining the fission cross section σ_x for neutrons of energy E and flux $\Phi(E)$ incident on a target is to measure the total number of produced fission fragments C_{ff}:

$$C_{\text{ff}}(E) = w(E) \left[\epsilon_{\text{ff}} \cdot \Phi(E) \cdot N_x \sigma_x(E) + \epsilon_{\text{ff}} \cdot \phi(E) \cdot \sum_{i=1}^{N_{\text{isotopes}}} N_i \sigma_i(E) + C_{\text{bkg}}(E) \right] , \tag{1}$$

where the target is composed by N_x atoms of the element of interest and of a number of contaminants isotopes N_i, and $w(E)$ and ϵ_{ff} are respectively the detector live time fraction and the fission fragment detection efficiency.

The term $C_{\text{bkg}}(E)$ comprises all types of background events and can be divided in three categories:

- fission events not produced by beam neutrons (e.g. spontaneous fissions and fission from environmental neutrons). These events are completely negligible in the fissionTPC experimental setup.
- fission events C_{bb} for which the inferred neutron energy (usually obtained via time-of-flight) does not correspond with the actual neutron energy. This includes fission events induced by in-beam down-scattered neutrons, room-return neutrons, neutrons from accelerator leakage current, and neutrons overlapping between pulses.
- non-fission events that are incorrectly identified as such. For the purpose of the fissionTPC, we explicitly discriminate between background events C_α from misidentified alphas (e.g. due to pile-up) from the actinide spontaneous decay and those from misidentified nuclear recoils C_r (e.g. from inelastic scattering on ^{16}O atoms in the gas or target materials). Particles from other beam-related processes like (n,α) that are incorrectly identified as fission fragments are also included in C_r.

To simplify the notation in Eq. 1 we assumed the spatial distribution of $\Phi(E)$ and N_x to be uniform. This assumption has been common in previous measurements with fission chambers. The fissionTPC plans to verify this assumption and therefore we must consider the general case where the beam and the target profile changes with position. In the this case, the beam flux and the target density can be written in terms of their normalized spatial distributions $\phi_E(X,Y)$ and $n(X,Y)$:

$$\Phi(E,X,Y) = K(E)\cdot\phi_E(X,Y) \qquad N_x(X,Y) = N_x\cdot n_x(X,Y)$$

where $K(E)$ and N_x are, the total number of neutrons and target atoms respectively. The term that enters the cross section equation is therefore:

$$N_x\cdot K(E)\cdot\int_{XY}\phi_E(X,Y)\cdot n_x(X,Y)$$

or its discretized equivalent if the XY space is divided in a finite number of bins $i = 1\ldots j$:

$$N_x\cdot K(E)\cdot\sum_{XY}\phi_{E,i}(X,Y)\cdot n_{x,i}(X,Y) \tag{2}$$

We assume here that the term in Eq. (1) related to the contribution from fissionable contaminants in the target material is negligible. This assumption will be verified during the analysis as described below. If needed, the effect of contaminants will be included explicitly and its uncertainty properly propagated.

The detector fission fragment efficiency ϵ_{ff} accounts for the fact that not all fission events produce fission fragments that are detectable and/or identifiable as such. Note that the efficiency may depend not only on the incident neutron energy but also (and more importantly) on the fission fragment energy and emission direction (polar angle).

In principle, Eq. (1) could be used to extract an absolute cross section for neutron-induced fission in the isotope x assuming all other terms in the equation can be measured or made negligible. Of all the terms, the total number of incident neutrons ($K(E)$ in Eq. (2)) is the most difficult to assess. For this reason, it is advantageous to measure the fission cross section for isotope x as a ratio with another cross section σ_{s}

Symbol	Description
σ_x	Unknown fission cross section to be measured (^{239}Pu)
σ_s	Fission cross section for the reference standard (^{235}U)
ϵ_{ff}^j	Efficiency in detecting fission fragments from the j side of the target
N_j	Total number of target atoms from the j side of the target
K_{att}	Beam attenuation in the target (ratio of integrated beam flux between side s and x)
$\sum_{XY}(\phi_{j,i} \cdot n_{j,i})$	Spatial overlap of beam and target (side j) normalized profiles
w_j	Live time on the j side of the target
C_{ff}^j	Measured number of fission fragments from the j side of the target
C_r^j	Number of beam-induced non-fission events contaminating the fission fragment sample
C_α^j	Number of alpha events contaminating the fission fragment sample
C_{bb}^j	Number of fission fragments for which the time-of-flight does not correlate with the incident neutron energy

Table 1: List of the terms in the cross section equation (3). Except for N_j, all terms depend on the incident neutron energy E.

that is used as a reference standard (usually ^{235}U(n,f) or ^{1}H(n,el)). If the experiment is built such that the same neutron flux impinge on both the isotope of interest and the standard reference, the total number of incident neutrons $K(E)$ cancels in the ratio. In reality, a correction factor $K_{\text{att}}(E)$ is needed to account for the absorbed or scattered neutrons in the upstream target material and in the backing material.

Combining all terms, we arrive at the equation for the cross-section ratio relative to a reference species s:

$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon_{ff}^s}{\epsilon_{ff}^x} \cdot \frac{N_s}{N_x} \cdot K_{\text{att}} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{C_{ff}^x - C_r^x - C_\alpha^x - C_{bb}^x}{C_{ff}^s - C_r^s - C_\alpha^s - C_{bb}^s}, \tag{3}$$

where the dependence on the incident neutron energy has been dropped for clarity.

It is therefore our goal to measure all of the quantities in Eq. (3) and their associated uncertainties. The required quantities are summarized in Table 1.

3 Overview of the analysis process for determining a cross-section result

As described above, the goal of NIFFTE is to measure fission cross-sections supported by a through understanding of associated systematic and statistical uncertainties. In this section we describe the sequence of steps that is required to take data inputs from the fissionTPC and associated ancillary systems and analyze these to produce the final cross-section result and uncertainty budget.

An overview of this process, as developed by the UWG, is shown in Fig. 1. There is no unique manner in which to approach this task but the structure described here is well suited to the major deliverable of the project: through understanding of the uncertainty associated with the determined cross-section. It is conceptually useful to break the analysis flow into four principal steps:

1. **Collection of Raw Inputs**

Inputs are defined here as the raw data collected by the fissionTPC, the Slow Control systems, and any ancillary measurements conducted to characterize system components. Examples of fissionTPC data include pad-level and cathode waveforms and timestamps. Slow Control data used for analysis include temperature and gas pressure histories. Ancillary measurements include target substrate and fissile deposit areal density, fissionTPC metrology.

2. **Determination of Event-Level Physical Quantities**

   This step involves the conversion of the above mentioned inputs into physically meaningful quantities at the event level. This is a multi-step process that combines many inputs and that requires careful validation. The primary example of this construct in NIFFTE is event reconstruction: pad and cathode waveforms are processed to determine quantities such as particle energy, incident neutron energy, particle direction, particle track specific ionization, particle initial position, etc. Obviously, many calibrations (drift speed, channel gains, timing offsets, ...) are required during this processing. The results of this processing require validation using dedicated measurements, e.g. measuring spontaneous fission branching ratio of ^{252}Cf.

3. **Determination of Cross-Section Quantities**

   Next, the set of event-level quantities determined above must be interpreted and the physical quantities required for a cross-section determination calculated, *along with their associated uncertainties*. An event selection process must be developed that acts on the processed event sample, and that sample manipulated to calculate the quantities of interest. Just as crucially, that selection process must be very well understood and a process developed to estimate the systematics uncertainties associated with each aspect of the selection process.

4. **Results**

   Finally, the data-set level physical quantities determined above must be combined to produce a cross-section result, along with a detailed breakdown of the associated total statistical and systematic uncertainties for that result.

While event-level quantities will have associated uncertainties, these will not typically propagate directly into the uncertainties associated with the cross-section quantities. Instead, a dedicated uncertainty analysis on the ensemble of event-level data will determine the uncertainties associated with these quantities. Of course, it will be critical to understand systematics at all levels of the analysis, e.g. position and angular resolution, when estimating the precision, and optimizing the values, of selection cuts.

In the the remainder of this document we examine each of these steps in more detail. The required processing and analysis steps are described and methods suggested for calculating and validating associated uncertainties, at both the event-level and cross-section-level, are given.

4 Inputs

Data inputs come from three sources: the fissionTPC itself, Slow Control, and ancillary measurements. As shown in Figure 1, these inputs feed into the reconstruction and ultimately are used in determining the final cross-section ratio.

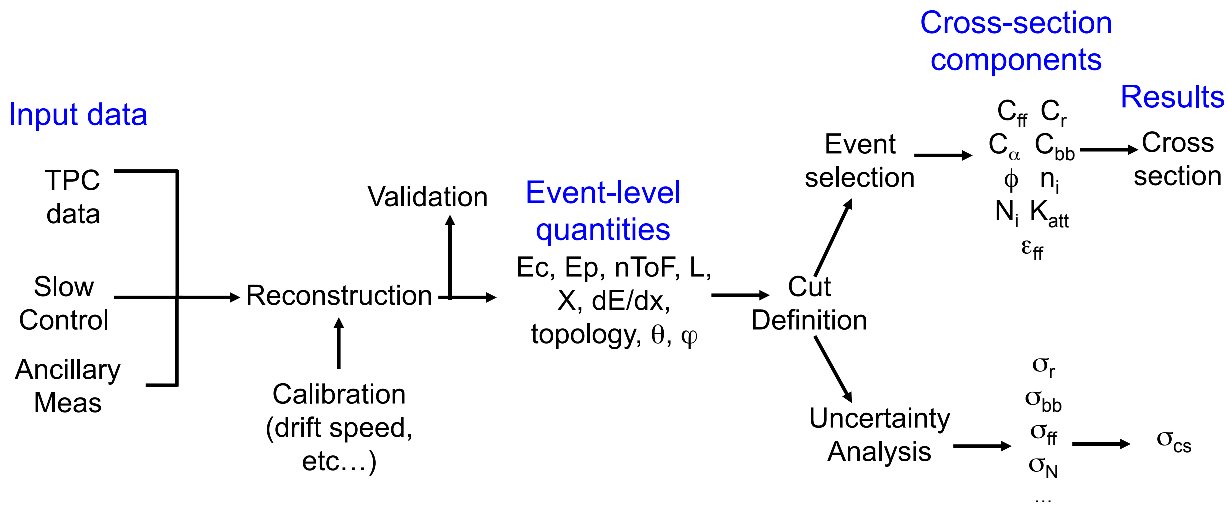

Figure 1: A flowchart describing the the analysis inputs and actions required to produce a cross-section measurement.

4.1 FissionTPC data

fissionTPC data consists of all data that flows through the EtherDAQ cards and subsequently recorded by the packet receiver. This raw data is sampled from over 6000 independent channels, as summarized in Table 2. Each channel is self triggered, meaning that whenever the trigger condition (threshold) for a particular channel is met, a digitized waveform (50 MHz sampling frequency) is acquired, sent to the packet receiver and recorded for offline analysis. Waveforms from pad plane channels are used to deduce the three dimensional distribution of ionization deposited in the active fissionTPC volume. The remaining data collected by the fissionTPC is used to for beam characterization (normalization and neutron time-of-flight).

Source	Signals	Channel Qty
Padplane Readout	5952	5952
Cathode Readout	1	20
Beam Timing	1	20
Fission Chamber	1	20
Total	5955	6012

Table 2: The fissionTPC data is readout from over 6000 independent channels described here.

4.2 Slow Control

Information used to make detailed corrections to the fissionTPC data is collected on a considerably slower timescale than the 50 MHz sampling mentioned above. Information recorded by the slow control system (Table 3) is recorded at around 1 Hz in a database to be used in conjunction with the fissionTPC data during offline analysis.

Source	Readings
Vessel Internal Temperature	8
External Temperatures	10
Gas Pressure	4
Data Rate	1
Shutter Status	1
High Voltage Potential	5
High Voltage Current	5
Micromegas Current	2
Gas Oxygen Content	1
Gas Water Content	1
...	...

Table 3: The slow control data shown here is used to apply macroscopic corrections to datasets and allow us to combine events that occur many hours apart into larger datasets.

4.3 Ancillary Measurements

Data required for analysis that changes at an even slower timescale than that recorded by the slow control system is measured and documented through our ancillary measurement system. This data primarily consists of as-built hardware (detector and target) parameters and are either hard-coded into analysis software or written to database tables which in turn are accessed during analysis. These ancillary parameters are summarized in Table 4.

Source	method
Drift Distance	direct measurement of detector
Field Cage Radius	direct measurement of detector
Target Source Strength	target assay
Target Source Contamination	material assay
Nominal Flight Path Length	direct measurement
Gas Composition	direct measurement
...	...

Table 4: Data that do not change on the day to week timescale are itemized here and recorded through our ancillary measurement system.

5 Determination of Event-Level Physical Quantities

In this section we describe how the input data is used to generate the event-level, calibrated, physical quantities which are necessary for calculating the quantities required for a cross-section measurement. During the reconstruction phase, raw data are processed and integrated with information from calibration to produce event-level calibrated quantities. As a side step, but equally important, the processing algorithms must be validated using both simulation and other measurements.

5.1 Reconstruction

The reconstruction process can be divided into two distinct tasks: determining the neutron time-of-flight from cathode signals and producing fitted particle tracks from pad-plane signals.

The neutron time-of-flight is determined by digitizing certain signals at 1 gigasample-per-second (GSPS). The beam signal from LANL, the cathode signal in the fissionTPC, and the fission chamber signal from downstream of the fissionTPC are all processed to determine the time-of-flight. The resolution of this measurement will determine the timing resolution for the final cross-section, and is a benchmark for the quality of the data.

Producing tracks is a more involved process with several steps. The raw fissionTPC data must be analyzed to produce 3D voxels, representing the origin of charge collected on the pads. A track finding algorithm should determine a set of voxels that constitute a single track. In order to better define the track, a fitting routine is used to assign a curve to the track. Once the track curve is defined it is possible to extract meaningful quantities related to the track which determine the particle type and trajectory.

5.1.1 Processing of Pad-plane Signals for Track Reconstruction

The raw fissionTPC data comprises a waveform from a given fissionTPC pad with an associated timestamp. This waveform, timestamp, and the independently determined electron drift speed are used to apportion the collected charge amongst 3D voxels. A track finding algorithm is then implemented to search for clusters of voxels. Typical methods include using Hough transforms and follow-your-nose algorithms to search for such clusters. Once a track has been identified it should be fit in order to determine its associated azimuthal and polar angles. Employing a Kalman filter is one common method for calculating the track fit, however, the curve will continue infinitely in both directions. Therefore, it is customary to truncate the track in a final vertexing step. Other algorithms exist for both track finding and fitting, such as a 3D edge finder and 3D least squares minimization respectively. Any combination of track finder and fitter can be used, and may be an approach to estimating the systematic uncertainty.

The track reconstruction process will result in the following event-level quantities:

1. Energy, E: the reconstructed particle energy, obtained first in ADC units and then converted using calibration information;
2. Angles, θ and ϕ: The polar and azimuthal angles of the track;
3. Length, L: the length of the reconstructed track, possibly corrected for diffusion;
4. Bragg Curve, dE/dx: the ionization profile of the track;
5. Vertex X,Y position
6. Vertex Z position, which is available only for particles that have a visible signal in the cathode

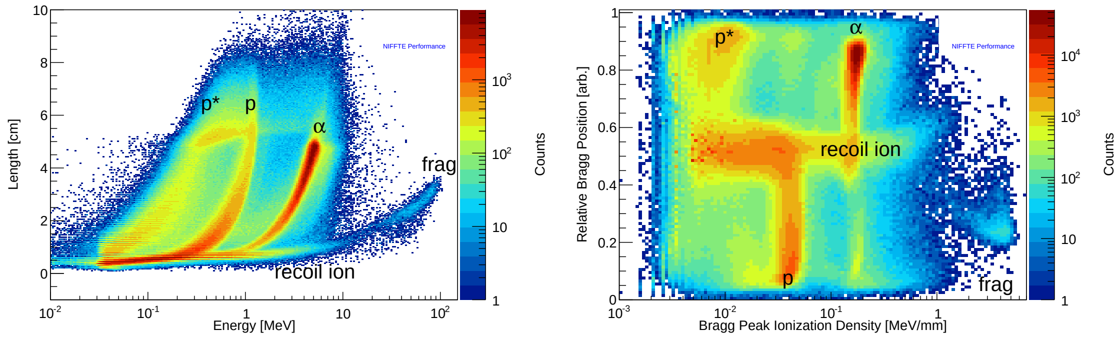

Figure 2: Reconstructed E vs L (left) and BP vs BV (right) plots showing the delineation of different particle types in different "bands" in this 4 parameter phase space.

5.1.2 Particle Identification

We can use reconstructed tracks to perform Particle Identification (PID). The value of the specific ionization, dE/dx, along the length of a track (the "ionization profile") is a near unique discriminant for the particle types of primary interest (protons, α-particles, and fission fragments). We have found that 4 parameters derived from reconstructed tracks can be used for PID:

1. Energy, E: The reconstructed particle energy;
2. Length, L: The length of the reconstructed track;
3. Bragg Value, BV: The maximum dE/dx value of the ionization profile;
4. Bragg Position, BP: The position of the maximum dE/dx value, relative to the length of the track (i.e. falls in the range $0 - 1$).

Examination of this 4 parameter phase space reveals regions populated by the different particle types of interest (Fig. 2). Examination of BP in concert with knowledge of the particle type also indicates particle direction. PID is performed by defining phase space regions associated with particular particle types.

Having defined PID selections, the central question to address, for each particle type of interest, is what is the efficiency for correct identification and the likelihood of incorrectly identifying another particle type as that of interest. These two identification parameters will be functions of particle energy. There are a number of ways to estimate these efficiencies, depending upon the particle types in question. The important cases are described below.

- **Selection of recoil protons**

  Recoil protons from (n,el) interactions that deposit all of their energy in the fissionTPC gas ("fully contained") will be used to measure the incident neutron beam profile (Sec. 6.3.2). These particles form a clear band in E vs L and BV vs BP plots. At low proton energy, this band merges with that due to recoils from heavier nuclei or degraded fission fragments, while at higher energies, it potentially merges with protons that are not fully contained. Since both of the "background" source of potential contamination are beam correlated, beam off data can not be used to estimate the frequency of mis-identification. Instead, selections that are placed 3σ from the the mean of contaminant distributions will be used. Similarly, in energy regions well away from contaminant particles, $\pm 3\sigma$ selection bands about the contained proton band will be used. The choice of 3σ is arbitrary and can be adjusted. The conversion from recoil proton energy within the selected energy range to neutron energy will be accomplished via a simulation study as described in Sec. 6.3.2.

- **Selection of target α-particles**

  α-particles from radioactive decay will be used to perform target autoradiographs as described in Sec. 6.3.1. These particles form a clear band in E vs L and BV vs BP plots. At low energy, this band merges with that due to recoils from heavier nuclei or degraded fission fragments. A similar procedure to that described above will be used to define a selection region for α-particles. Examination of data from ^{252}Cf or off-beam will allow estimation of fission fragment contamination, independent of other beam induced recoil nuclei.

- **Selection of target fission fragments**

  Fission fragments will be used to determine C_{ff}, as described in Sec. 6.2. Again, these particles form a clear band in E vs L and BV vs BP plots. This band is also populated by beam induced nuclear recoils. At low energies α-particles can also contribute. For ^{239}Pu targets, α-particle pileup may also be a concern. Selection regions will be defined as described above. Beam-off ^{252}Cf and beam-on blank target data can be used to estimate contamination fractions. Simulation studies can be used to estimate fission fragment acceptance.

5.1.3 Reconstruction of Time-Of-Flight from Cathode Signals

The neutron time-of-flight (nTOF) is used to determine the incoming neutron energy. In fissionTPC experiments done at WNR, the nTOF is defined as the time it takes a neutron to travel from the spallation target (WNR Target 4) to the target foil in the fissionTPC. Ideally this would uniquely define the neutron's energy, details of how and why this is not the case will be discussed in the next section. Here we will focus on our ability to measure the time-of-flight and the uncertainties associated with those measurements. In general, our nTOF measurement consists of two sub measurements

1. The time-of-flight start which we refer to as M_0 (derived from Macro-pulse start) is created by a "pick-off circuit" provided by the LANSCE facility. This signal represents the start of a macro pulse, which in turn defines the start of each micro-pulse providing a measurement of the neutron production time.

2. The time-of-flight stop, or T_0 signal, is extracted from the cathode signal. As the ionization left by a fission products begins to drift through the chamber it induces a current on the cathode which is readout. This cathode signal provides the measurement of when the neutron that induced the fission reached the target foil.

The time between these two signals is the uncalibrated nTOF. Both signals have unique propagation delays, and have an arbitrary but fixed (algorithm dependent) offset from the true times they are measuring. The propagation delays and arbitrary offsets are accounted for in a single nTOF offset. The offset is measured by setting the nTOF for gamma induced fission events to D/c, where D is the distance from the spallation target to actinide target and c is the speed of light. Gamma rays and neutrons are simultaneously (to much better than our timing resolution) produced when the proton-bunch hits the spallation target.

5.1.4 Timing resolution

The gamma ray burst from the proton bunch interacting with the spallation target is created over a few picoseconds, while our timing resolution is on the order of nanoseconds. Our timing resolution can be directly extracted from the width of the gamma-fission peak in the nTOF spectrum. Contributions to our ultimate timing resolution come from a number of sources:

1. Uncertainty associated with M_0 timing algorithm.
2. Uncertainty associated with T_0 timing algorithm.
3. Finite volume of spallation target.
4. Finite volume of actinide deposit.
5. Proton bunch width.

Of these uncertainties, the first two are dominant and result in a timing resolution on the order of a few nanoseconds. The TOF can be directly converted to an incident neutron energy once the path length is known. Simple uncertainty propagation yields the energy uncertainty for a given event.

5.2 Calibrations

There are many different calibrations that are performed on the fissionTPC, but they fall into three main categories: energy, time, and setup.

Charge is collected on a pad-by-pad basis in the fissionTPC and recorded in an analog-to-digital converter (ADC) in arbitrary units. Each pad and ADC combination might have a different gain, and thus could generate a different ADC value for the same amount of charge. Introducing radon gas (^{220}Rn) into the fissionTPC and comparing with simulation, allows to obtain a relative gain-match of all the pads. Once the relative pad-to-pad calibration is achieved, the absolute energy scale could be set using the known energy from a spontaneous alpha source. Because of the effects of diffusion and channel thresholds the measured energy varies with track polar angle. A linear energy scaling should be sufficient for our purposes.

The fast signals from the cathode are also used to extract an energy quantity E_c for each detected event. Since multiple ADCs are used to sample the same signal, it is relatively easy to match their relative gain. The absolute energy scale can also be extracted using a known alpha peak.

Timing calibration between the various signals is accomplished in two steps. First, the different timing offsets that might be present between the clock on each EtherDAQ card is computed at the beginning of each run and corrected for during the analysis. This ensure that all cards are synchronized relative to one card (usually the cathode card). The timing offset of the reference card could change under certain conditions (timestamp reset and power cycling) that are recorded in the run database. This offset can be corrected for by aligning the photo-fission peak across data sets.

Other important calibrations pertain directly to the physical setup of the fissionTPC. The neutron flight path length is determined by placing a carbon filter upstream of the fissionTPC. There is a well known scattering resonance in carbon for neutrons of a specific energy with carbon. By analyzing the time-of-flight data, it is possible to determine how long it takes these neutrons to reach the experimental setup, and hence the length of the flight path. This information is then used to calibrate the TOF spectrum.

The charge drift speed in the fissionTPC is critical for reconstructing tracks. Various methods are under study to extract the drift speed directly from the data. The most promising one is based extracting timing information for fission fragments from both anode and cathode waveforms and, after correcting for diffusion, using those to calculate the drift time. Another approach is based on geometric considerations for tracks originating at the target and extend beyond the vessel boundaries.

The physical pad orientation and drift field uniformity will can be calibrated by creating well defined tracks using a 4 mJ laser. The laser will ionize the gas along a known track, thus, deviations in the reconstructed track will help to illuminate drift field non-uniformities. Additionally, this can be used to help calibrate the physical location of the pads, as well as providing information about charge diffusion in the gas. While the laser system is under active development, it may not be possible to deploy it within the exact same experimental setup that is operating at LANL. Extrapolating to the actual operating conditions is likely going to be based on simulations and will introduce some additional uncertainty in the FY15 analysis.

Another important calibration pertains the measurement of the flightpath length. which is used to calibrate the nTOF and is further used to translate a given nTOF to actual energy. The flight path length is calculated by looking at the different nTOF values for neutrons of different but well-known energies. This is accomplished by placing a carbon filter in the beam and identifying nTOF's associated with neutron-carbon resonances in the nTOF spectrum. The ability to measure the flightpath length is therefore limited by our ability to extract the nTOF for these resonances and therefore ultimately by the timing resolution and the collected statistics.

For all calibrated quantities it will be important to study their stability. For example, ADC gains are temperature dependent and could therefore fluctuate in time. The drift speed, field uniformity, and diffusion may all vary due to changes in the gas properties or drift field itself. It will be important to monitor these values over the course of the experiment in order to merge the data.

5.3 Validation

Validating the quantities and algorithms mentioned in this section is necessary given the central goal of the project - a precision measurement. Simulation will be used throughout the analysis process, but at this point will be critical in understanding and correcting for effects like diffusion, pileup, electric field non-uniformity, etc. Where possible, measurements using radioactive sources will also be used for validation. For example, a thin ^{252}Cf source should not only provide an isotropic distribution of fission fragments but can also be used to detect both fission fragments simultaneously, which would help to validate both tracking and vertexing. Reproducing the expected results for such a measurement would serve as a strong endorsement of the reconstruction and calibration processes.

6 Prescriptions for Cross-Section Quantity and Uncertainty Determination

Here we discuss how we measure and assess the uncertainty of the various physical quantities required for the cross-section determination. These are the quantities that appear in the cross-section formula (Eq. (3)) and are listed in Table 1.

6.1 Incident Neutron Energy via Time-of-Flight

Section 5.1.3 explains how the neutron energy is determined from the time-of-flight method with the fissionTPC at WNR. The neutron energy resolution comes directly from the timing resolution and the classical kinetic energy of the neutrons. The timing resolution is calculated from the width of the photo-fission peak; further details are given in Section 5.1.4.

There are several reasonable approaches for determining the contribution from the uncertainty in the neutron energy to the final cross-section. The most straightforward approach is to calculate the shift in the amplitude of the cross-section when evaluated at each extreme the neutron energy bins. Following this prescription, the contribution to the final uncertainty can be assigned on a bin-by-bin basis. The uncertainty will be greatest in regions where the cross-section gradient is large. An alternative method would be to implement a Monte Carlo simulation to estimate this uncertainty, using the calculated energy resolution as an input, as described in Sec. 7

6.2 Fission Fragment Identification and C_{ff}

The number of fragments identified in volume i is denoted C^i_{ff} and is tightly coupled to a choice of analysis cuts. When determining this and most of the quantities detected in the remaining section, certain cuts must be chosen and fixed to proceed to a self consistent result. These cuts correspond to defining selection criteria comprised of some or all of the following event level physics quantities

1. Total reconstructed pad plane energy.
2. Total reconstructed cathode energy.
3. PID phase space parameters (as defined in Sec. 5.1.2)
4. Track start location.
5. Track end location.
6. Track direction.
7. Event time with respect to the macro-pulse start.

We must find a balance between minimizing statistical uncertainty on the number of fragments found by accepting the most fragments possible while simultaneously minimizing the the systematic uncertainties associated with the cuts. Generally, the track direction will be used to define a fiducial volume which rejects regions of high field distortions and large "straggling" effects from the finite thickness of the actinide deposit and backing.

After a set of cuts has been defined, the uncertainty of each cut parameter must be examined and used to determine the overall systematic uncertainty associated with the final fragment count C_{ff}. The method described later in section 7 should be used to determine the systematic uncertainty of each PID cut component which can then combined to determine the overall uncertainty. Alternatively, once the component uncertainties have been determined the methods of section 7 can be applied many time each time varying all cut parameters within their respective uncertainties creating an ensemble from which the total C_{ff} systematic uncertainty can be extracted.

6.3 Spatial Product of Beam and Target Profiles

A central component of a cross-section determination is knowledge of the number of initiating and target particles available to participate in the reaction of interest. By construction, the ratio method eliminates the need for absolute knowledge of these quantities. However, non-uniformities in either fissile material target used in a ratio measurement can break the assumed symmetry on which the systematic uncertainty cancellation rests. Furthermore, if the targets are non-uniform and non-identical, any non-uniformity in the beam must now also be accounted for. This is accounted for by the following term in Eq. 3:

$$\frac{\sum_{XY}(\Phi_{b,i} \cdot n_{b,i})}{\sum_{XY}(\Phi_{a,i} \cdot n_{a,i})} \tag{4}$$

Here we describe how each profile is measured using the set of reconstructed tracks and how the uncertainty on that quantity is to be estimated.

6.3.1 Target Profile, n_i

In this section we limit discussion to the ^{239}Pu/^{235}U ratio determination. Other actinide ratios will be a simple extension of the technique described here, while the ratio to ^{1}H will have significant differences. The actinide spatial profile from each side of the ^{239}Pu/^{235}U target will be determined from α-particle autoradiograph data. This data will be collected at different times due to the difference in activity between the two species:

- for ^{235}U dedicated beam-off data will be used;
- for ^{239}Pu dedicated beam-off data with a pulse derived trigger mask will be used. Alternately, beam-on data windowed on a period well after the beam macro pulse could be used.

An event selection acting on track direction, energy and PID will be developed to produce a sample of α-particle decays. Reconstruction studies to determine the position, angular, and energy resolution for α-particles will be required for the uncertainty determination that follows. Additionally, studies that demonstrate the correspondence in tracking performance for α-particles and fission fragments will be required. That is, the correspondence between selection efficiency for α-particles and fission fragments must be demonstrated. Finally, reconstruction studies must also demonstrate that the fissionTPC response (selection efficiency) is uniform as a function of spatial position.

6.3.2 Beam Profile, Φ_i

The neutron beam spatial profile will be determined from proton recoil interactions in the fissionTPC gas. The start vertex of recoil protons gives the interaction position and therefore corresponds to the spatial distribution of incident neutrons. Only those recoil protons that deposit all energy in the fissionTPC gas will be used - the Bragg peak at the end of the proton track allows a robust determination of which end of the track is the start vertex. The variation in dE/dx along tracks where the Bragg peak is not recorded is too small to allow good direction determination.

This requirement causes the distribution of neutron energies and interaction positions included in the beam profile sample to be complicated, and most readily accessible via simulation. Understanding of this distribution will allow study of the beam uniformity as a function of energy. Since not all beam energies will be accessible in this profile measurement technique, quantification of the extent to which the profile varies with energy will be important.

Since the beam profile is not measured directly at the target positions, simulation derived corrections for scattering in fissionTPC and target substrate materials may be necessary. The two beam profile measurements possible are:

- in the fissionTPC gas upstream of the target, where scattering has only occurred in the fissionTPC vessel and upstream fissionTPC gas
- in the fissionTPC gas downstream of the target, where scattering has occurred in the fissionTPC vessel, the upstream fissionTPC gas, the target actinides and substrate, and the downstream fissionTPC gas.

A simulation based correction can be validated by comparing the prediction for the downstream profile (based on a correction to the measured upstream profile) to that measured. Simulation-based corrections for the beam incident on the two actinide surfaces can then be used for the beam-target spatial overlap quantity.

6.3.3 Beam/Target Spatial Overlap and Uncertainty Determination

With the normalized spatial profiles in hand, determination of the spatial overlap quantity is straightforward. Deviation of this quantity from unity would be worthy of note, since it would indicate an effect not accounted for in previous fission chamber measurements. Observation of a significant variation would be a powerful validation of the power the tracking capability of the fissionTPC provides.

Of course it is necessary to determine an uncertainty associated with the overlap quantity to assess the significance of any observed deviation from unity. The greater information provided by the fissionTPC provides the means for a detailed uncertainty determination, that does not rely on uniformity and cancellation arguments. Just as any spatial non-uniformities could introduce uncertainty in the ratio method when using a fission chamber without position resolution, non-uniformities at distance scales below the position resolution of the fissionTPC can introduce uncertainty.

Therefore, the uncertainty in the overlap quantity will be determined using a variational Monte Carlo study using knowledge of the position resolution of the fissionTPC for proton recoils and alpha particles. Profiles will be generated by Monte Carlo with spatial features characterized by a length scale parameter. For each length scale parameter, an ensemble of profiles will be generated and the overlap quantity calculated. The width of the distribution of overlap parameters is an estimate of uncertainty introduced by features on this scale. The value of this uncertainty at length scale at which the fissionTPC can no longer resolve the variations will be used as our estimate of the uncertainty associated with this quantity in the cross-section determination.

6.4 Fission Fragment Detection Efficiency ϵ_{ff}

To measure the fission fragment detection efficiency ϵ_{ff} we will use a thin backed target as seen in Figure 3. To keep the notation simple, in the following we will drop the subscript ff. Given a fission event occurs in

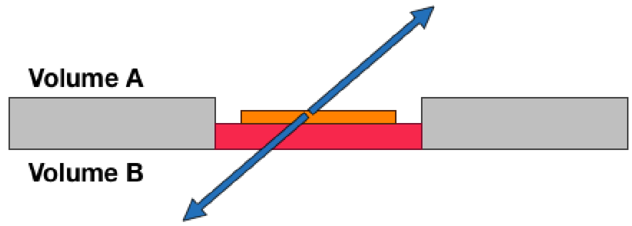

Figure 3: When using a thin carbon backing on the actinide target foil, fission fragments are visible in both volumes. By counting fragments in each volume it is possible to quantify the detection efficiency and, under certain assumptions, the deconvolve the effects of the backing material.

volume i, ϵ_i is the probability that a fragment is detected and identified as a fragment in the correct volume i. To begin we define the following events

$$A \equiv \text{Fragment identified in Volume 1}$$
$$B \equiv \text{Fragment identified in Volume 2}$$

we can then write

$$\begin{aligned} \mathbb{P}(A) &= \epsilon_1 \\ \mathbb{P}(\bar{A}) &= 1-\epsilon_1 \\ \mathbb{P}(B) &= \delta\cdot\epsilon_2 \\ \mathbb{P}(\bar{B}) &= 1-\delta\epsilon_2 \end{aligned}$$

where δ represents the effect of carbon backing. The fragments detected (our observable) can then be written as

$$\begin{aligned} C_1 &= C_T\cdot\epsilon_1 \\ C_2 &= C_T\cdot\delta\cdot\epsilon_2 \\ C_{12} &= C_T\cdot\delta\cdot\epsilon_1\epsilon_2 \end{aligned}$$

where C_T are the number of fissions that actually occur, C_i is the number of fissions only detected via a fragment in volume i, and C_{12} is the number of fissions detected with fragments in both volumes. Next we consider various probabilities

$$\begin{aligned} \mathbb{P}\left(A\cap B\right) &= \delta\cdot\epsilon_1\epsilon_2 \\ \mathbb{P}\left(\bar{A}\cap B\right) &= \left(1-\epsilon_1\right)\delta\cdot\epsilon_2 \\ \mathbb{P}\left(A\cap\bar{B}\right) &= \epsilon_1\left(1-\delta\cdot\epsilon_2\right) \end{aligned}$$

which can also be written in terms of our observables C_1, C_2, C_{12}, and the unknown C_T.

$$\begin{aligned} \mathbb{P}\left(A\cap B\right) &= C_{12}/C_T \\ \mathbb{P}\left(\bar{A}\cap B\right) &= C_2/C_T \\ \mathbb{P}\left(A\cap\bar{B}\right) &= C_1/C_T. \end{aligned}$$

Finally by looking at specific ratios, then non-observable term C_T will cancels and we are left with

$$\frac{\mathbb{P}\left(\bar{A}\cap B\right)}{\mathbb{P}\left(A\cap B\right)}=\frac{C_2}{C_{12}}=\frac{\left(1-\epsilon_1\right)\delta\cdot\epsilon_2}{\delta\cdot\epsilon_1\epsilon_2}=\frac{1}{\epsilon_1}-1$$

therefore

$$\boxed{\epsilon_1=\frac{C_{12}}{C_1+C_{12}}} \tag{5}$$

Analogously, using the ratio

$$\frac{\mathbb{P}\left(A\cap\bar{B}\right)}{\mathbb{P}\left(A\cap B\right)}$$

we conclude

$$\boxed{\delta\cdot\epsilon_2=\frac{C_{12}}{C_2+C_{12}}} \tag{6}$$

Finally if we assume $\epsilon_1\approx\epsilon_2$, we can conclude

$$\boxed{\delta\approx\frac{C_1+C_{12}}{C_2+C_{12}}} \tag{7}$$

The uncertainty in ϵ will be determined via error propagation of the uncertainties for the C terms.

6.5 Fission Fragments with Time-of-Flight not Correlated with Incident Neutron Energy $C_{\mathbf{bb}}$

There are a number of situations in which the incident neutron energy extracted from the observed ToF does not correspond with the actual neutron energy. In the equation (3), these are accounted for by the terms C_{bb} and must be accurately investigated to avoid systematic bias in the cross-section measurement. These effects are:

- pulse overlapping (wrap around) neutrons
- room returns
- neutrons from accelerator leakage current
- in-beam down-scattering

here we briefly describe each of these processes and how they will be characterized.

Wrap around neutrons

Due to the pulsed structure of the neutron source, a wrap around effect occurs when slow neutrons from one pulse overlap with the fast neutrons of the following pulse. Their ToF (time from the start of the last pulse) is therefore incorrect measure of the neutron energy. This effect is stronger for fissile isotopes where the fission cross-section is large for low neutron energies. For ^{238}U and other non-fissile isotopes, the wrap around contribution is negligible.

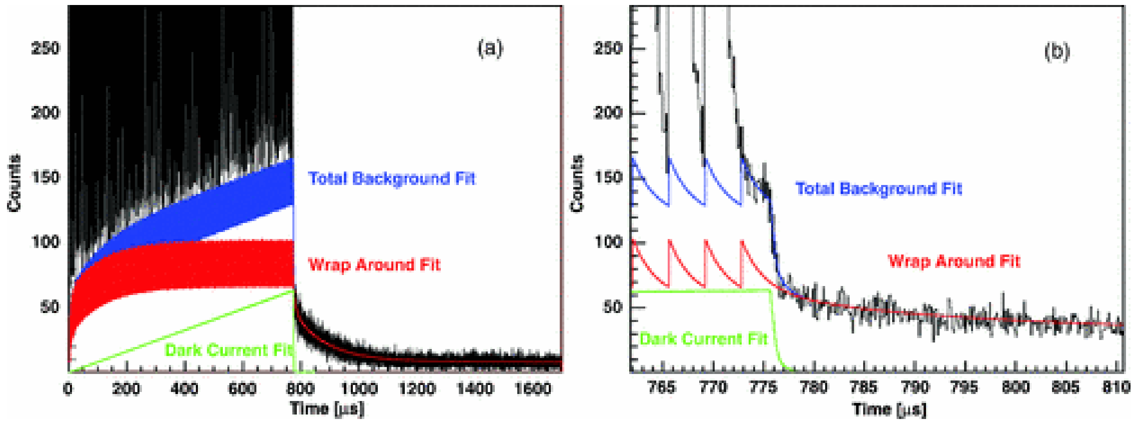

Figure 4: Background functions fit to TDC's in previous fission chamber measurment [5]. Panel (a) shows the background functions both during and after a macro-pulse, and panel (b) shows a closer view of the end of the macro-pulse.

Wrap around neutrons contribute to a tail of fission events after each micropulse. This contribution dies away at the end of the macro pulse and can be directly measured in that region. In previous work [5], the tail of the macropulse was fit with an empirical function of three exponentials, as shown in Fig.4. The systematic uncertainty was extracted from the uncertainty in the fit parameters and resulted in a $\sim 1\%$ contribution.

In order to reduce the systematic uncertainty below 1%, MCNP simulations will be used to produce a detailed distribution of the wrap-around neutrons, thus allowing to better take into account the fine structure of the neutron spectrum. The simulated function will be fit to the data with only a free normalization parameter .

The micropulse spacing can be changed from 1.8 μs to 3.6 μs to better measure the effect of wrap around neutrons and thus validate the MCNP model.

Room returns

Neutron room returns will be evaluated using MCNP and validated against the witness foil measurement. The use of simulation and data should allow to distinguish the room returns contribution from the wrap around neutrons.

Neutrons from accelerator leakage current

Neutrons generated by the proton dark current were observed in past experiments with fission chambers. Changes in the accelerator operation has greatly reduced the dark current and it should not be present in the fissionTPC data, except for limited time intervals. A fission chamber with a ^{238}U target is installed downstream of the fissionTPC and allows to monitor the absence of dark current events. The fission chamber data will be analyzed to look for dark current and, if necessary, fissionTPC data sets where dark current is observed will be discarded. In the unlikely case where a significant fraction of the data were affected by dark current, instead of discarding those data sets, a correction factor will be calculated by extrapolating the fission chamber data to the fissionTPC via simulations.

In-beam down-scattering

While traveling from the spallation target some neutrons will down-scatter along the beam path before inducing fission in the fissionTPC. Because of this process, the ToF associated with the fission event will not correspond to the incident neutron energy. A direct measurement of the in-beam down-scattering would require mono-energetic neutrons. In order to estimate the required correction as a function of beam energy, MCNP simulations will be used. A preliminary calculation shows that the in-beam contribution is below the 1% level except at the lowest ($<$ 1MeV) neutron energies.

As for all the previous terms above, the systematic uncertainty associated with this correction depends primarily on our level of confidence in the MCNP simulation which can be assessed during the simulation validation phase.

6.6 Fission Fragments Contamination from Alphas C_α

In Equation (3), the term C_α represents alphas from the actinides spontaneous decays that are incorrectly identified as fragments. In time-of-flight space, the alpha background from $^{239}\mathrm{Pu}$ is a constant background since the alpha rate is uncorrelated with the neutron beam. The spontaneous fission rate from $^{239}\mathrm{Pu}$ is $\approx 10\ \mathrm{fissions/s/kg}$, so for our target deposits which are $< 1\ \mathrm{mg}$, can be neglected. The fragment contamination from $^{239}\mathrm{Pu}\ \alpha's$ can be directly measured can be directly measured by looking at fragments during "beam-off" periods. Depending on the level of room return, dark current and wrap around a non-zero (and possibly non-negligible) fission rate may exist between macro pulses. The C_α quantity should be extracted from either shutter closed or pre- or post-beam data runs. In the 2014 data-run we have already taken data using a mocked-up trigger mask that will be used for this purpose, however until C_α is fully quantified and understood, we should continue to take data during beam down-times with a mocked up trigger mask signal. When measured during beam down periods, the primary uncertainty will be from our ability to run the fissionTPC in the exact same conditions as during beam and our ability to normalize from no-beam data runs to beam on run conditions on a run by run basis.

6.7 Fission Fragments Contamination from Beam-Induced Non-Fission Events C_r

In Equation (3), the terms C_r accounts for contamination of our fission fragment sample from neutron induced nuclear recoils on the various fissionTPC components, in particular oxygen atoms in the gas, target and other parts. It also includes contamination of the fission fragment sample from other beam-induced processes like (n,α) in the actinides or other detector components. These events are directly measured by taking in-beam data in absence of any fissionable target i.e. with the blank target. Most of these nuclear recoils are expected to be produced by high-energy neutrons and should be therefore removed with a simple ToF cut (FY15 deliverable focuses on cross-section up to 20 MeV). By applying the same cuts that are used in the Pu/U thick target analysis to the blank data, the acceptance of those cuts in eliminating nuclear recoils can be estimated. The C_r terms are obtained by scaling the number of nuclear recoils passing the cuts in the blank data to those in the Pu/U target data. This normalization is done using the beam halo outside of the active target area.

The uncertainty associated with the C_r comes from:

1. the statistics in the blank target data

2. the sensitivity of C_r on the cuts (in particular the PID selection and the z-coordinate of the events which is used to distinguish between target and gas events)
3. the normalization factor, which depends in turn on: the beam profile, the O_2 content in the target material, and the gas density fluctuations.

Additional confidence in this quantity and its uncertainty could be gained by comparison with simulations.

6.8 Number of Target Atoms N_i and Target Isotopic Purity

The total number of target atoms of the desired isotope is given in Equation (3) by N_i.

Targets are made by the group at Oregon State University which provides also several associated data:

- Average aerial density
- The isotopic abundances of the actinide nuclides in the svn log target is specified by either mass spectroscopy or alpha spectroscopy on the source material used to prepare the targets
- Measurement of non-uniformity performed on test targets shows variation $< 1.2\%$ over the target area.

In-situ autoradiograph counting alpha particles with the fissionTPC complements the information provided by OSU on the average aerial density. Additionally, this method will take advantage of the excellent tracking of the fissionTPC in order to study the target uniformity.

The uncertainty in the total number of target atoms will depend largely on the statistical uncertainty due to the number of alpha particles detected, as well as the uncertainty in the purity of the target.

For low levels of contamination it might be possible to neglect the contamination entirely. In the case of well defined regions of contamination, it might be best to place a fiducial cut on the contamination to remove it from further analysis.

The contribution of contaminants can be estimated from their fission cross-section evaluation. The error of this contribution is estimated from the contaminant level accuracy and the evaluation cross-section uncertainty. If not negligible, this contribution is subtracted from the total fission counts and its uncertainty propagated accordingly.

6.9 Detector Live Time w_i

In Equation (3), the terms w_i represent the live times of the data acquisition system for recording an event in a given volume of the fissionTPC.

Careful consideration still needs to be given to calculating this quantity and estimating its uncertainty. Given the way that the fissionTPC and its electronics operates it is expected that the pad planes be essentially 100% live, with any potential dead time due being connected with the cathode signal. One approach might involve performing an analysis to verify that spontaneous alphas or fissions (e.g. from ^{252}Cf) are emitted according to a Poisson distribution. Issues to consider might include:

- Definition of dead time for the fissionTPC

- Signal rise time - multiple signals in trapezoidal filter width
- Dead time induced on cards when self-triggered

6.10 Standard Cross-Section σ_s

It is customary to measure the cross-section of interest, σ_x in Equation (3), relative to a standard cross-section, σ_s. For the present campaign of measurements, the cross-sections will be measured relative to that of $^{235}\text{U}(n, f)$, which is a standard at 0.0253 eV and from 0.15 to 200 MeV [6]. There is great interest in using the ^{1}H(n,n') standard cross-section since it has lower uncertainties that the $^{235}\text{U}(n, f)$ cross-section. However, at the present time, such a hydrogenous target is still in the developmental phase.

6.11 Beam attenuation in target K_{att}

By measuring the cross-section as a ratio for two actinides deposited back-to-back on the same substrate exposed to the same beam avoids the inherent difficulty of requiring knowledge of the absolute number of neutrons in the beam. Instead, only a correction factor K_{att} is needed to account for the absorbed or scattered neutrons in the upstream actinide and in the backing material. Previous measurements in fission chambers have shown that K_{att} is very close to 1.

The primary method to extract this quantity is to use validated MCNP simulations. Validation of the MCNP model can be done by comparing the beam flux and profile in the upstream and downstream volumes, as already required in the context of analyzing the beam profile term. The contribution from scattering in the target backing material could be further estimated during measurements with the blank target.

Uncertainty in this correction term comes from primarily from the simulation accuracy in modeling the beam profile.

7 Cross-section Ratio and Total Uncertainty

The concept of "results" can vary with context and mean different things to different people. For the fissionTPC project, in this context our results consist of

1. A measured energy differential actinide cross-section with respect to a standard reference cross-section. For FY15, we will report
$$\frac{^{239}\mathrm{Pu(n,f)}}{^{235}\mathrm{U(n,f)}}$$
over the 100 keV to 25 MeV incident neutron energy range using a logarithmic 50 bins per decade binning scheme.
2. A set of fully quantified systematic uncertainties, including correlations in the form of a covariance matrix. For FY15, we will report the systematic uncertainty associated with
   (a) Target actinide areal density uniformity.
   (b) Spatial uniformity of neutron fluence integrated across a range of energies yet to be determined.

(c) Determination of the total number of fission fragments C^i_{ff}.

in each energy bin using the same binning structure as the reported cross-section ratio.

Speaking in a generic sense, we have a set of input parameters $\vec{x}$ and a set of output parameters $\vec{y}$ related by some function $f(\vec{x})$. For the purposes of a cross-section ratio, the inputs are the quantities discussed in section 6 and the function is given by (3). We will determine the uncertainty σ_{y_j} by observing how the associated output y_j changes when the input quantity x_i is varied within it's uncertainty σ_{x_i}. Lets consider the concrete example of nTOF where the uncertainty on time-of-flight is given by a Gaussian with a standard deviation of 3 ns. In this case one could apply a random offset drawn from a normal random distribution with standard deviation of 3 ns to each time-of-flight used in the calculation. The updated time-of-flights will result in a slightly different distribution of C_{ff}, C_r, etc. across the energy bins and result in changes to the calculated cross-section ratio. Repeating this procedure an appropriate number of times will result in an ensemble of possible "outcomes" used to deduce the systematic uncertainty of the cross-section from the uncertainty of an underlying quantity (in this case nTOF). It is important to note that while in this case the uncertainty on the nTOF input parameter is Gaussian and constant across incident neutron energies, the resulting uncertainty is neither Gaussian nor constant across energies. Furthermore, in cases where we have sufficient statistics, it is possible to bypass the ensemble step by applying a Gaussian smear to the input data and directly calculate a change in the output.

8 Simulations

Simulations play an important role throughout the analysis process, as outlined in the previous sections. A comprehensive discussion on the development of the simulations for the fissionTPC is beyond the scope of this document and is subject to ongoing work. Nonetheless, we would like to review here some of the key aspects of the simulation work and how it relates to the cross section analysis and uncertainty estimation.

The simulation framework for the NIFFTE fissionTPC is divided in four areas:

1. Modeling of neutron source and transport, primarily using MCNP
2. Modeling of particles interaction in the detector and charge production, primarily using GEANT4
3. Modeling of the electron drift and detector response to ionization signals, primarily using custom developed Monte Carlo software
4. Toy Monte Carlo simulations aimed at studying specific uncertainty terms

In all cases, the modeling effort includes, when possible, independent validation of the simulation and an estimation of the confidence level in reproducing the measured processes.

8.1 MCNP Modeling of Neutron Source and Transport

MCNP is the platform of choice for simulating neutrons. In the context of the fissionTPC, MCNP will be used to simulate the spallation neutron source, the beam transport to the detector and in the experimental area, and to calculate the neutron interactions in the detector. The output from MCNP simulation could become the input for subsequent simulation steps with GEANT4 or other tools.

MCNP efforts include:

1. evaluation of the beam flux attenuation factor K_{att}
2. evaluation of the correction factor from in-beam down-scattered neutrons (part of C_{bb})
3. evaluation of the contamination from neutrons overlapping between micropulses (part of C_{bb})
4. evaluation of room returns (part of C_{bb})
5. evaluation of the distribution of neutrons interactions in the TPC gas (supports beam profile measurement)
6. study of effect of proton beam size and timing on the ToF spectrum
7. study of effect of secondary fission events induced by fission neutrons
8. advise on improvements to experimental setup for future beam runs

MCNP simulation work will be prioritized to support initially the FY15 milestones. Particular emphasis is therefore given to supporting the determination of the beam profile. For FY15, it may be acceptable to evaluate C_{bb}, in particular the wrap-around contributions, using the same approach as in fission chambers. Similarly, K_{att} can be calculated but without in depth evaluation of the uncertainty if needed.

In any case, the MCNP model needs first to be validated. One possible validation method is to compare the predicted vs measured ratio of fissions in the target and in the witness foils. Validation of the correct neutron beam spectrum and profile at the spallation target could be done based on previous measurements with fission chambers (e.g. ^{237}Np measurement in [5]).

8.2 GEANT4 Modeling of Particles Interaction in the Detector

For the GEANT4 model, in FY15 priority will be given to supporting validation of the mechanics used in extracting the event-level quantities described in section 5, in particular the tracking and vertexing algorithm, and the development of the particle identification cut parameters. For tracking, the work will be coupled with the modeling of the detector response, described in the next section, that accounts for non-ideal response (e.g. electric field non-uniformities, thresholds, gain non-uniformity, ...). While studying particle identification, uncertainties in how well GEANT4 is able to produce the dE/dx of heavy particles like fission fragments and nuclear recoils will need to be taken into account.

In addition, as discussed in section 6.3.2, GEANT4 simulations will play an important role in understanding the distribution of protons produced from neutron scattering on the fissionTPC gas, which is required to extract the beam profile. In this case, MCNP will be used to provide (n,p) interaction points from which the GEANT4 simulation then creates the proton track in the gas.

Validation of the GEANT4 simulation could be done using for example ^{252}Cf calibration data. Data from a ^{220}Rn gas source mixed in the fissionTPC gas would provide good validation of the simulations in modeling interaction in the gas rather than from the target.

8.3 Modeling of Detector Response

Modeling of the detector response is achieved through custom simulations to describe the following aspects:

- charge drift and diffusion
- non-uniform electric field
- signal generation in the micromegas and cathode

These simulations are necessary to prove that the collaboration fully understands the response of the detector in all its details. In addition, it could provide uncertainty estimations or correction factors for certain effects like, for example, the presence of non-uniform electric field.

8.4 Toy Monte Carlo Simulations

Toy Monte Carlo simulations will be used for specific variational studies where one wants to explore the impact on the cross section or its uncertainty of a certain parameter. An example of this is given in section 6.3.3 for studying the impact of non-uniformities in the target and beam profile that are below the fissionTPC position resolution.

9 Conclusions

This document attempts to provide a cohesive and credible path forward for analyzing the fissionTPC data to meet the project's deliverables for FY15. More specifically, it is meant to guide the analysis efforts and thus help its coordination and prioritization. Indeed, each of the cross-section physical quantities detailed in section 6 is effectively an analysis task, along with others leading to extracting and validating the event-level quantities. While the work on these tasks will be spread as appropriate across all interested members of the collaboration, the UWG will continue to provide the unifying perspective and direction, with its members as liaisons of the various tasks.

Therefore, the next steps for the UWG are:

- ensure all high-priority tasks for FY15 are assigned and staffed
- work with task leader to develop WBS supporting information, in particular identifying requirements when needed
- coordinate and integrate the various activities toward the cross-section and uncertainty analysis
- update and maintain the collaboration ”uncertainty plot”

While we tried to be as comprehensive as possible in the time available, this document does not aim to be the final word on the methodology for extracting the fission cross-section and uncertainties with the fissionTPC. As the analysis progresses and further understanding of the detector operation is achieved, there will certainly be the need to refine the prescriptions given here.

In addition to the value for the collaboration work, the understanding gained during the process of producing this document is valuable also in front of the broader fission community. The accuracy goal of the project, and the need to verify directly previous experimental assumptions shape the complexity of the experimental setup and data analysis. The use of a fissionTPC for (n,f) cross-section measurements is a major leap over previous experimental technologies. In a similar way, the data analysis suggested here attempts to systematically look at all potential sources of uncertainty in a way that has been fully achieved before.

Acknowledgments

The authors are thankful for the encouragement, inputs and support of the entire NIFFTE collaboration in preparing this document.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344. This work has also benefited from the use of the Los Alamos Neutron Science Center at the Los Alamos National Laboratory. This facility is funded by the US Department of Energy and operated by Los Alamos National Security, LLC under contract DE-AC52-06NA25396. Report LLNL-TR-666664

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